

21cm Absorption by Compact Hydrogen Disks Around Black Holes in Radio-Loud Nuclei of Galaxies

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The clumpy maser disks observed in some galactic nuclei mark the outskirts of the accretion disk that fuels the central black hole and provide a potential site of nuclear star formation. Unfortunately, most of the gas in maser disks is currently not being probed; large maser gains favor paths that are characterized by a small velocity gradient and require rare edge-on orientations of the disk. Here we propose a method for mapping the atomic hydrogen distribution in nuclear disks through its 21cm absorption against the radio continuum glow around the central black hole. In NGC 4258, the 21cm optical depth may approach unity for high angular-resolution (VLBI) imaging of coherent clumps which are dominated by thermal broadening and have the column density inferred from X-ray absorption data, $\sim 10^{23} \text{ cm}^{-2}$. Spreading the 21cm absorption over the full rotation velocity width of the material in front of the narrow radio jets gives a mean optical depth of ~ 0.1 . Spectroscopic searches for the 21cm absorption feature in other galaxies can be used to identify the large population of inclined gaseous disks which are not masing in our direction. Follow-up imaging of 21cm silhouettes of accelerating clumps within these disks can in turn be used to measure cosmological distances.

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I. INTRODUCTION

The discovery of an edge-on H_2O maser disk in the nucleus of NGC 4258 [1, 2] provides the best current evidence for a nuclear black hole outside the Milky-Way galaxy. The radial extent of the maser ring, ~ 0.14 – 0.28pc , and its measured Keplerian rotation profile between ~ 770 – 1100 km s^{-1} , imply a central black hole mass $M \approx 4 \times 10^7 M_\odot$ [3]. To obtain large maser gains, any such disk needs to be viewed at a nearly edge-on orientation with the maser clumps lying along the lines of minimal variation in the line-of-sight velocity [4, 5]. Given the small geometric likelihood of edge-on orientations, the subsequent discovery of maser disks in the nuclei of other galaxies [6, 7, 8], demonstrated that cold nuclear disks must be ubiquitous. The maser clumps potentially mark the outskirts of the accretion disk that fuels the central black hole in these galaxies.

The Milky Way galaxy does not show evidence for a compact nuclear disk but instead features young massive stars at an orbital radius of $\lesssim 0.3 \text{ pc}$ from the central black hole, SgrA* [9, 10]. These stars could not have formed in a central molecular cloud because of the strong tidal field of SgrA* [11]. Instead, they are conjectured to have formed in a cold compact disk, at a sub-parsec distance from SgrA*, where the disk self-gravity was important [12, 13, 14]. For the generic radial profile of a viscous accretion disk, the Toomre Q -parameter is indeed expected to approach unity at the required distance scale [15, 16, 17, 18], making the disk unstable for fragmentation. This coincidence could also explain the clumpy nature of maser disks at a rotation velocity of $\sim 10^3 \text{ km s}^{-1}$ [14]. Elsewhere in our Galaxy, masers are observed to be associated with regions in which massive

stars form [19, 20]. It is therefore likely that the observed maser disks in external galactic nuclei represent sites of star formation [14]. The abundance of maser disks implies that galactic nuclei experience common episodes of disk formation, during which massive stars – like those observed near SgrA*, are born. Winds from these massive stars or supernova explosions (supplemented by additional feedback from the accreting nuclear black hole) could have dispersed the central disk in the Milky-Way galaxy on a short timescale of $\lesssim 10^7$ years. In the future, a new disk might form when fresh cold gas will assemble once again around SgrA*.

Little is known observationally about the global gas distribution in the observed maser disks [3]. Here we propose to map atomic hydrogen in nuclear disks through its 21cm absorption of background radio glow around the black hole. It is known that radio-emitting plumes (which define the base of large-scale jets [21]) exist around NGC 4258 (see Fig. 1 in Ref. [3]), but the angular extent of the coronal radio emission at 1.42GHz and its potential absorption by the disk have not been explored as of yet in the published literature [22]. In §2 we calculate the expected optical depth for 21cm absorption in nuclear gaseous disks. This absorption signature could be identified through Very Long Baseline Interferometry (VLBI) observations of regions where the continuum backlighting is sufficiently bright.

In principle, the 21cm absorption by nuclear disks can be mapped at high angular and spectral resolutions. The velocity and acceleration of clumps within the disk can then be used to infer the angular diameter distance to the sources, as demonstrated for maser clumps in NGC 4258 [2, 23, 24, 25]. The 21cm absorption feature can also be searched for spectroscopically (without spatial

resolution) in a survey over a large number of compact radio sources. Because the 21cm absorption signature would appear for arbitrary disk inclination, a dedicated search for this signature would be more likely to find nuclear disks than searches for masers which are limited to edge-on orientations of the disks. Follow-up VLBI imaging of disks could then be used to infer the central black hole mass for a large sample of galaxies.

II. OPTICAL DEPTH OF COMPACT NUCLEAR DISKS

The radiative transfer equation for the intensity I_ν of the 21cm line along a particular line-of-sight reads [26],

$$\frac{dI_\nu}{ds} = \frac{\phi(\nu)h\nu}{4\pi} [n_2 A_{21} - (n_1 B_{12} - n_2 B_{21}) I_\nu], \quad (1)$$

where ν is the photon frequency, ds is the path element, $\phi(\nu)$ is the line profile function normalized by $\int \phi(\nu) d\nu = 1$ (with an amplitude of order the inverse of the frequency width of the line, $\Delta\nu$), subscripts 1 and 2 denote the lower and upper levels of the line, n denotes the number density of atoms at the different levels, and A and B are the Einstein coefficients for the transition between these levels. We make use of the standard relations: $B_{21} = (g_1/g_2)B_{12}$ and $B_{12} = (g_2/g_1)A_{21}n/I_\nu$, where g is the spin degeneracy factor of each state. For the 21cm transition, $A_{21} = 2.85 \times 10^{-15} \text{s}^{-1}$ and $g_2/g_1 = 3$ [27]. The relative populations of hydrogen atoms in the two spin states defines the so-called spin temperature, T_s , through the relation, $(n_2/n_1) = (g_2/g_1) \exp\{-E/kT_s\}$, where $E/k = 0.068 \text{K}$ is the transition energy. In the regime of interest here, $T_s \gg E$ and so $[(g_2/g_1)(n_1/n_2) - 1] \approx E/kT_s$, and $n_2 \approx \frac{3}{4}n_H$, where n_H is the total number density of hydrogen atoms. Moreover, the brightness of the spontaneous 21cm emission is too weak to be detectable. We therefore ignore the first term in the square brackets of Eq. (1) and consider the absorption signature of the gas against a bright radio continuum glow in the background. Defining the optical depth along a ray as $\tau = -\Delta \ln I_\nu$, we get

$$\tau(\nu) = \frac{3}{32\pi} \frac{h^3 c^2 A_{21}}{E^2} [\nu \phi(\nu)] \frac{N_H}{kT_s}, \quad (2)$$

where $N_H = \int n_H ds$ is the column density of hydrogen.

To get an estimate for the average optical depth value across the line profile, we write $\nu \phi(\nu) = (\Delta\nu/\nu)^{-1}$, where $(\Delta\nu/\nu_0) = (\Delta v/c)$, is the fractional Doppler width of the line, corresponding to a velocity spread Δv among the absorbing atoms. The minimum line width attainable is dictated by the spread in the thermal velocities of the atoms, for which [26], $\Delta v = v_{\text{th}} = (2kT/m_H)^{1/2}$, where m_H is the hydrogen atom mass. A larger width can be induced by a gradient in the bulk velocity of the gas

along the line-of-sight and is calculated in the Sobolev approximation [37]. When the 21cm line is optically-thin ($\tau \lesssim 1$), the absorption signal obtains a width that reflects all the contributing gas elements within the angular resolution and frequency band of the observations.

Substituting all the coefficients into Eq. (2) yields,

$$\tau = 0.7 \left(\frac{N_H}{10^{23} \text{cm}^{-2}} \right) \left(\frac{T_s}{8 \times 10^3 \text{K}} \right)^{-1} \left(\frac{\Delta v}{10 \text{km s}^{-1}} \right)^{-1}. \quad (3)$$

The specific numerical values that were substituted on the right-hand-side of Eq. (3), correspond to the expected parameters of the atomic hydrogen disk in NGC 4258 [3]. X-ray observations of this system indicate a hydrogen column density of $\sim 10^{23} \text{cm}^{-2}$ [30]. Based on the observed X-ray luminosity of NGC 4258 and the warped geometry of its disk, the gas is expected to be predominantly atomic (rather than molecular) outside a radius $\sim 0.3 \text{pc}$ (see Fig. 23 in Ref. [3]). Theoretical calculations [5] suggest that the atomic hydrogen [38] in the disk of NGC 4258 has an asymptotic temperature $\sim 8000 \text{K}$, providing a thermal velocity width of $v_{\text{th}} \approx 10 \text{km s}^{-1}$. At the high densities under consideration, we assume that the spin temperature T_s is in collisional equilibrium with the kinetic temperature of the gas. High resolution imaging of nuclear disks can therefore be used to constrain their density and temperature distributions through Eq. (3).

The scale height of a thin accretion disk, h , is expected [31] to be a fraction $\sim (v_{\text{th}}/v_\phi)$ of its radius r , where $v_\phi(r) = (GM/r)^{1/2}$ is the rotation speed at r for a black hole mass M . A line of sight which crosses the disk at an angle θ relative to the normal to the disk samples a spread in the line-of-sight bulk velocity that is $\leq (2h/\cos\theta)[(dv_\phi/dr)\sin\theta] = (\sin^2\theta/\cos\theta)v_{\text{th}}$. For the warped (bowl-shaped) maser region of NGC 4258, the value of $\cos\theta \approx 0.3$ [3] yields $\Delta v \sim (1-3) \times v_{\text{th}}$.

In order for VLBI imaging to reach the thermal broadening minimum of Δv , a particular spatial resolution element needs to be dominated by a single clump of gas with a coherent bulk velocity. Such a clump would have a small line-of-sight bulk velocity if it is located in front of the black hole and up to the full rotation speed on the side. If the clump fills only a fraction f of the source area within the resolution element, then τ will be reduced by a factor of f . For the diffuse gas in the disk, the spatial resolution required to achieve the thermal width minimum is of order the disk scale height, $h \sim (v_{\text{th}}/v_\phi)r$. This resolution scale corresponds to $\sim 10^{-2}r \sim 3 \times 10^{-3} \text{pc}$ for NGC 4258. At a wavelength of 21cm and a source distance of 7.2Mpc, this resolution requires an unrealistic baseline of $\sim 5 \times 10^5 \text{km}$, larger by a factor of 40 than the diameter of the Earth. Thus, a terrestrial VLBI will resolve the disk in NGC 4258 only around and outside the maser region ($r \gtrsim 0.14 \text{pc}$). Coincidentally, this is indeed the region expected to be dominated by atomic

hydrogen [3]. An analogous disk around a quasar black hole whose mass M is larger by two orders of magnitude than in NGC 4258, could in principle be resolved out to a distance of ~ 1 Gpc.

We conclude that the high value of the optical depth in Eq. (3) applies to silhouettes of coherent clumps in which thermal broadening dictates the velocity spread Δv . Such clumps are expected to exist outside the maser region, where the Toomre- Q parameter is of order unity or lower [14]. If individual clumps of atomic hydrogen are not resolved or if the disk is smooth, then the optical depth would be diluted over a broader velocity width. In general, the absorption depth at a given frequency bin scales as the fractional (brightness-weighted) area of the continuum source over which hydrogen atoms resonate with photons in the observed frequency bin.

Under a uniform background illumination, the absorption spectrum of an unresolved circular disk can be obtained through a sum over concentric rings in the disk plane. We assume that the normal to the disk plane is inclined at an angle θ relative to the line-of-sight. A single optically-thin ring with a circular rotation velocity $v_\phi(r) = (GM/r)^{1/2}$ and a radius r , gives a U-shaped spectral profile in terms of $-1 < \delta(\nu) < 1$ [32],

$$\tau(\nu, r) = \frac{\tau_{\text{ring}}(r)}{\pi(1 - \delta^2)^{1/2}}, \quad (4)$$

where $\delta = [(\nu - \nu_0)/\nu_0]/[0.5\Delta v/c]$, $\Delta v = 2v_\phi(r) \sin \theta$, and

$$\begin{aligned} \tau_{\text{ring}}(r) &= 0.44 \times 10^{-2} \left(\frac{N_H(r)}{10^{23} \text{ cm}^{-2}} \right) \left(\frac{T_s}{8 \times 10^3 \text{ K}} \right)^{-1} \\ &\times \left(\frac{v_\phi(r) \sin \theta}{800 \text{ km s}^{-1}} \right)^{-1}. \end{aligned} \quad (5)$$

The total absorption feature of an unresolved disk can be obtained by summing over all the rings in which atomic hydrogen resides, weighted by the brightness distribution of the backlighting at $\nu_0 = 1.42\text{GHz}$.

For an arbitrary background illumination, the net deficit in the fractional spectral intensity across the area S of an unresolved optically-thin source is given by,

$$\frac{\Delta I_S}{I_S}(\nu) = - \frac{\int_S I_\nu(x, y) \tau(\nu, x, y) dx dy}{\int_S I_\nu(x, y) dx dy}, \quad (6)$$

where (x, y) are the sky coordinates and the unabsorbed continuum source can be assumed to have a smooth (typically power-law, $I_\nu \propto \nu^\alpha$) spectrum across the absorption line profile in the numerator. For a thin disk which is not perfectly edge-on, the exact expression for the optical depth $\tau(\nu, x, y)$ in Eq. (2) can be approximated as the thermally broadened value in Eq. (3) at the Doppler shifted frequency $\nu_0[1 - v_\parallel/c]$, where $v_\parallel(x, y)$ is the line-of-sight component of the bulk velocity of the gas. Clearly, in order for the spectral deficit to be noticeable, a dominant component of the radio emission needs to origi-

nate behind the absorbing disk. If the background illumination originates from a narrowly collimated jet (as indicated by the 22GHz image of NGC 4258), then the absorption feature will be characterized by the low line-of-sight velocity spread (Δv) of the material in front of the jet. In this case, the spectral deficit will be larger than the deficit associated with the full velocity spread of the disk. For the narrow jets of NGC 4258 [3], we estimate $\Delta v \sim 100 \text{ km s}^{-1}$ and $\tau \sim 0.1$. A dedicated search for the 21cm spectroscopic feature in other compact radio sources can be used to identify new nuclear disks in distant galaxies.

III. DISCUSSION

The parameters of the maser disk in NGC 4258 imply that atomic hydrogen within the compact gaseous disks in galactic nuclei can produce measurable 21cm absorption against the backlight of continuum radio emission around the central black hole. For NGC 4258, the 21cm optical depth may approach unity in silhouettes of coherent clumps which are dominated by thermal broadening and have the column density inferred from X-ray absorption data [30]. Spreading the absorption across the rotation velocity width of the material in front of the collimated jets in NGC 4258 results in an expected optical depth of ~ 0.1 .

More than half of all nuclear H_2O megamasers show X-ray absorption with column densities $N_H \sim 10^{24} - 10^{25} \text{ cm}^{-2}$ (see Ref. [33] and Fig. 7 in Ref. [34]), at which the optical depth for 21cm absorption might exceed unity. High-resolution VLBI images of 21cm absorption can be used to map the distributions of the density, temperature, and line-of-sight velocity of atomic hydrogen in nuclear disks. Such maps could show direct evidence for spiral arms [35], which are conjectured to exist based on the latest maser data in NGC 4258 [2, 25]. More generally, the maps hold the potential for testing current models of accretion disks, shedding light on the geometry of obscured (Compton-thick) quasars, and improving our understanding of star formation in galactic nuclei.

A comprehensive search for a spectroscopic absorption feature in radio-loud nuclei of galaxies can be used to find a large number of inclined gaseous disks which are not masing in our direction. The improved statistics of known nuclear disks would provide better understanding of the duty cycle of black hole fueling and star formation in galactic nuclei.

Remote atomic hydrogen within the host galaxy would also result in absorption but will be limited to low-velocity widths. The compact nuclear disk is expected to dominate the wings of the 21cm absorption profile which extend out to velocity offsets of $\pm 10^3 \text{ km s}^{-1}$. Follow-up imaging of the nuclear disk can be used to separate out extended galactic absorption.

VLBI measurements of the velocity and acceleration of coherent hydrogen clumps within the disk can be used to infer the angular diameter distance to the source, as demonstrated with maser clumps [2, 23, 24, 25]. Detection of suitable radio sources out to sizeable redshifts could potentially place new constraints on the equation of state of the dark energy through the dependence of the angular diameter distance on source redshift [23]. The selection of a large number of suitable targets would be a particularly attractive goal [36] for the planned Square Kilometer Array [39].

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